

CHAPTER 7

GENERATORS

7-1. Generator usage

Electric generators are devices that convert energy from a mechanical form to an electrical form. This process, known as electromechanical energy conversion, involves magnetic fields that act as an intermediate medium.

a. Generator types. There are two types of generators: alternating current (AC) and direct current (DC). A generator may provide electrical power as the primary power source, standby power source, or emergency power source. It may be part of the primary electrical distribution system (above 600 volts) or part of the secondary distribution system (600 volts and below).

b. Energy conversion. The generator provides electrical power through the introduction of mechanical energy to a prime mover that takes this mechanical energy and converts it to electrical energy. Power companies accomplish this by using fossil and/or nuclear power to drive the prime mover. Large industrial sites can use their waste exhaust for such purposes. In addition, geothermal and wind turbines can also accomplish the same goal. However, for most Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) sites, diesel powered generators will supply electricity on demand when local power is not available. The less volatile diesel fuel feeds the diesel engine that drives the prime mover. As the prime mover rotates, it drives the generator rotor causing magnetic lines of force to be cut by electrical conductors. Electrical energy is thereby produced by electromagnetic (EM) induction.

c. Power generation. The generator's operation is based on Faraday's law of EM induction. In brief, if a coil (or winding) is linked to a varying magnetic field, then an electromotive force (EMF) or voltage is induced across the coil. Thus, generators have two essential parts: one creates a magnetic field, and the other where the EMFs are induced. The magnetic field is typically generated by electromagnets (thus, the field intensity can be adjusted for control purposes), whose windings are referred to as field windings or field circuits. The coils where the EMFs are induced are called armature windings or armature circuits. One of these two components is stationary (stator), and the other is a rotational part (rotor) driven by an external torque. Conceptually, it is immaterial which of the two components is to rotate because, in either case, the armature circuits always "see" a varying magnetic field. However, practical considerations lead to the common design that for AC generators, the field windings are mounted on the rotor and the armature windings on the stator. In contrast, for DC generators, the field windings are on the stator and armature on the rotor.

7-2. Generator operation

A generator consists of a number of conducting coils and a magnetic field. The coils are called the armature. Relative motion between the coils and magnetic field induces voltage in the coils. This action is called EMF. An AC generator needs a separate DC source to feed the magnetic field. The required DC is provided by an external source called an exciter. Usually, the exciter is a small DC generator that is driven by the generator rotor. The exciter may be mounted on the rotor shaft or rotated by belt-drive. Some generating systems use a static, solid-state exciter to provide DC. A voltage regulator controls the

induced voltage by regulating the strength of the EM field established by the exciter. Frequency is controlled by the speed at which the prime mover rotates the rotor.

7-3. Generator types

Depending on the type of generating equipment employed, the electrical energy produced is either DC or AC.

a. AC generators. AC generators are considered either brush or brushless, based on the method used to transfer DC exciting current to the generator field. In addition, AC generators are classified as salient-pole or nonsalient-pole depending on the configuration of the field poles. Projecting field poles are salient-pole units and turbo-type (slotted) field poles are nonsalient-pole units.

b. DC generators. DC generators are classified as shunt, series, or compound wound. Most DC generators are the compound wound type. Shunt generators are usually used as battery chargers and as exciters for AC generators. Series generators are sometimes used for street lights. The EMF induced in a DC generator coil is alternating. Rectification is needed to direct the flow of current in one direction. The generator rotating commutator provides the rectifying action.

7-4. AC generators

AC generators are classified as single-phase or polyphase. Variations include three-phase generators used as single-phase units by insulating and not using one phase lead. Since the lead is unused, it is not brought out to a terminal. The kilowatt rating is reduced from that of the three-phase unit as limited by the amount of current carried by a coil. A generator designed only for single-phase operation usually does not have coils in all of the armature slots because end coils contribute little to the output voltage and increase the coil impedance in the same proportion as any other coil.

a. Single-phase generators. A single-phase generator is usually limited to 25 kW or less and generates AC power at a specific utilization voltage. Single-phase alternators are usually used in smaller systems. Terminal voltage is usually 120 volts. A variation is the three wire, single-phase alternator has three power terminals; one from each end of the armature coil and one from the neutral. Terminal voltage is usually 120 volts from the midpoint to either end of the armature coil and 240 volts between the two ends. The load is connected between the two outside wires or between either outside wire and neutral, depending upon the voltage required by the load.

b. Polyphase generators. Polyphase generators produce two or more alternating voltages (usually two, three, or six phases). Two-phase power is used in only a few localities. Six phase is primarily used for operation of rotary converters or large rectifiers. Three-phase alternators are the most widely used for power production. Polyphase alternators have capacities from 3 kW to 250,000 kW and voltage from 110 V to 13,800 V. Two general types of three-phase alternator windings are the delta winding used in three wire, three-phase alternators, and the star or wye winding used in four wire, three-phase types.

c. Damper windings. Damper windings on the rotor stabilize the speed of the AC generator to reduce hunting under changing loads. If the speed tends to increase, induction generator action occurs in the damper windings. This action places a load on the rotor, tending to slow the machine down. If the speed tends to decrease, induction motor action occurs in the damper winding, tending to speed the machine up. The windings are copper bars located in the faces of the rotor pole pieces. Mounted parallel to the rotor axis, the bars are connected at each end by a copper ring.

d. Synchronous generators. AC generators that operate at a speed that is exactly proportional to the frequency of the output voltage are synchronous generators. Synchronous generators are usually called alternators. Today, most electric power is produced by synchronous generators. Synchronous generators rotate at a constant speed, called synchronous speed. This speed is dictated by the operating frequency of the system and the machine structure. There are also AC generators that do not necessarily rotate at a fixed speed such as those found in windmills (induction generators); these generators, however, account for only a very small percentage of today's generated power.

(1) The rotor consists of a winding wrapped around a steel body. A DC current is made to flow in the rotor winding (or field winding), and this results in a magnetic field (rotor field). When the rotor is made to rotate at a constant speed, the three stationary windings experience a periodically varying magnetic field. Thus, EMF is induced across these windings. This EMF is AC and periodic; each period corresponds to one revolution of the rotor. Thus, for 60-Hz electricity, the rotor has to rotate at 3600 revolutions per minute (rpm); this is the synchronous speed of the given machine. Because the windings are displaced equally in space from each other (by 120 degrees), the EMF waveform is displaced in time by 1/3 of a period. The machine is therefore capable of generating three-phase electricity. The machine has two poles since its rotor field resembles that of a bar magnet with a north pole and a south pole.

(2) When the stator windings are connected to an external (electrical) system to form a closed circuit, the steady-state currents in these windings are also periodic. These currents create magnetic fields of their own. Each of these fields is pulsating with time because the associated current is AC; however, the combination of the three fields is a revolving field. This revolving field arises from the space displacements of the windings and the phase differences of their currents. This combined magnetic field has two poles and rotates at the same speed and direction as the rotor. In summary, for a loaded synchronous (AC) generator operating in a steady state, there are two fields rotating at the same speed: one is due to the rotor winding and the other due to the stator windings.

(3) It is important to observe that the armature circuits are in fact exposed to two rotating fields, one of which, the armature field, is caused by and in fact tends to counter the effect of the other, the rotor field. The result is that the induced EMF in the armature can be reduced when compared with an unloaded machine (i.e., open-circuited stator windings). This phenomenon is referred to as armature reaction. The EMF induced in a stator winding completes one period for every pair of north and south poles sweeping by; thus, each revolution of the rotor corresponds to two periods of the stator EMFs. If the machine is to operate at 60 Hz, then the rotor needs to rotate at 1800 rpm. In general, a p -pole machine operating at 60 Hz has a rotor speed of $3600/(p/2)$ rpm. That is, the lower the number of poles is, the higher the rotor speed has to be. In practice, the number of poles is dictated by the mechanical system (prime mover) that drives the rotor.

(4) Steam turbines operate best at a high speed; thus, two- or four-pole machines are suitable. Machines driven by hydro turbines usually have more poles. Usually, the stator windings are arranged so that the resulting armature field has the same number of poles as the rotor field. In practice, there are many possible ways to arrange these windings. Geometry suggests that, at any time instant, equal EMFs are induced across the windings of the same phase. If the individual windings are connected in series, their EMFs add up to form the phase voltage.

e. Auxiliary devices. In addition to the basic components of a synchronous generator (rotor, stator, and their windings), there are auxiliary devices which help maintain the machine's operation within acceptable limits. Three such devices are mentioned here: governor, damper windings, and excitation control system.

(1) A governor is to control the mechanical power input P_{in} . The control is via a feedback loop

where the speed of the rotor is constantly monitored. For instance, if this speed falls behind the synchronous speed, the input is insufficient and has to be increased. This is done by opening up the valve to increase the steam for turbogenerators or the flow of water through the penstock for hydrogenerators. Governors are mechanical systems and therefore have some significant time lags (many seconds) compared to other EM phenomena associated with the machine. If the time duration of interest is short, the effect of governor can be ignored in the study; that is, P_{in} is treated as a constant.

(2) Damper windings (armortisseur windings) are special conducting bars buried in notches on the rotor surface, and the rotor resembles that of a squirrel-cage-rotor induction machine. The damper windings provide an additional stabilizing force for the machine when it is perturbed from an equilibrium. As long as the machine is in a steady state, the stator field rotates at the same speed as the rotor, and no currents are induced in the damper windings. That is, these windings exhibit no effect on a steady-state machine. However, when the speeds of the stator field and the rotor become different (because of a disturbance), currents are induced in the damper windings in such a way as to keep the two speeds from separating.

(3) Modern excitation systems are very fast and quite efficient. An excitation control system is a feedback loop that aims at keeping the voltage at machine terminals at a set level. From a system viewpoint, the two controllers of excitation and governor action rely on local information (machine's terminal voltage and rotor speed). In other words, they are decentralized controls. For large-scale systems, such designs do not always guarantee a desired stable behavior since the effect of interconnection is not taken into account in detail.

f. Induction generators. A three-phase induction machine is similar to a synchronous machine, but the former has a much simpler rotor circuit. A typical design of the rotor is the squirrel-cage structure, where conducting bars are embedded in the rotor body and shorted out at the ends. When a set of three-phase currents (waveforms of equal amplitude, displaced in time by one-third of a period) is applied to the stator winding, a rotating magnetic field is produced. Currents are therefore induced in the bars, and their resulting magnetic field interacts with the stator field to make the rotor rotate in the same direction. In this case, the machine acts as a motor since, in order for the rotor to rotate, energy is drawn from the electric power source.

(1) When the machine acts as a motor, its rotor can never achieve the same speed as the rotating field (this is the synchronous speed) for that would imply no induced currents in the rotor bars. If an external mechanical torque is applied to the rotor to drive it beyond the synchronous speed, however, then electric energy is pumped to the power grid, and the machine will act as a generator.

(2) An advantage of induction generators is their simplicity (no separate field circuit) and flexibility in speed. These features make induction machines attractive for applications such as windmills.

(3) A disadvantage of induction generators is that they are highly inductive. Because the current and voltage have very large phase shifts, delivering a moderate amount of power requires an unnecessarily high current on the power line. This current can be reduced by connecting capacitors at the terminals of the machine. Capacitors have negative reactance; thus, the machine's inductive reactance can be compensated. Such a scheme is known as capacitive compensation. It is ideal to have a compensation in which the capacitor and equivalent inductor completely cancel the effect of each other. In windmill applications, for example, this faces a great challenge because the varying speed of the rotor (as a result of wind speed) implies a varying equivalent inductor.

7-5. DC generators

To obtain DC electricity, one may prefer an available AC source with an electronic rectifier circuit. Another possibility is to generate DC electricity directly. Although the latter method is becoming obsolete, it is still important to understand how a DC generator works. As in the case of AC generators, a basic design will be used to explain the essential ideas behind the operation of DC generators.

a. Basic theory. The stator of the simple machine is a permanent magnet with two poles labeled N and S. The rotor is a cylindrical body and has two (insulated) conductors embedded in its surface. At one end of the rotor the two conductors are connected to a pair of copper segments; these semicircular segments are mounted on the shaft of the rotor. Hence, they rotate together with the rotor. At the other end of the rotor, the two conductors are joined to form a coil. Assume that an external torque is applied to the shaft so that the rotor rotates at a certain speed. The rotor winding formed by the two conductors experiences a periodically varying magnetic field, and hence an EMF is induced across the winding.

b. Commutation. This voltage periodically alternates in sign, and thus, the situation is conceptually the same as the one encountered in AC generators. To make the machine act as a DC source, viewed from the terminals, some form of rectification needs be introduced. This function is made possible with the use of copper segments and brushes. Each copper segment comes into contact with one brush half of the time during each rotor revolution. The placement of the (stationary) brushes guarantees that one brush always has positive potential relative to the other. For the chosen direction of rotation, the brush with higher potential is the one directly beneath the N-pole. (Should the rotor rotate in the reverse direction, the opposite is true.) Thus, the brushes can serve as the terminals of the DC source. In electric machinery, the rectifying action of the copper segments and brushes is referred to as commutation, and the machine is called a commutating machine.

c. DC voltage. The voltage across the unloaded terminals is not a constant. A unidirectional current can flow when a resistor is connected across the terminals of the machine. The pulsating voltage waveform generated by the simple DC machine usually cannot meet the requirement of practical applications. An improvement can be made with more pairs of conductors. These conductors are placed in slots that are made equidistant on the rotor surface. Each pair of conductors can generate a voltage waveform but there are time shifts among these waveforms due to the spatial displacement among the conductor pairs. For instance, when an individual voltage is minimum (zero), other voltages are not. If these voltage waveforms are added, the result is a near constant voltage waveform. This improvement of the DC waveform requires many pairs of the copper segments and a pair of brushes.

d. Armature reaction. When the generator is connected to an electrical load, load currents flow through the rotor conductors. Therefore, a magnetic field is set up in addition to that of the permanent magnet. This additional field generally weakens the magnetic flux seen by the rotor conductors. A direct consequence is that the induced EMF is less than those in an unloaded machine. Similar to the case of AC generators, this phenomenon is referred to as armature reaction, or flux-weakening effect.

e. Brushes. The use of brushes in the design of DC generators can cause a serious problem in practice. Each time a brush comes into contact with two adjacent copper segments, the corresponding conductors are short-circuited. For a loaded generator, such an event occurs when the currents in these conductors are not zero, resulting in flashover at the brushes. This means that the life span of the brushes can be drastically reduced and that frequent maintenance is needed. A number of design techniques have been developed to mitigate this problem.

f. Excitation. The stator winding is called the field winding, which produces excitation for the machine. The current in the field winding is adjusted by means of a variable resistor connected in series with this winding. It is also possible to use two field windings in order to have more flexibility in control. The use of field winding(s) on the stator of the dc machine leads to a number of methods to produce the magnetic field. Depending on how the field winding(s) and the rotor winding are connected, one may have shunt excitation, series excitation, etc. Each connection yields a different terminal characteristic.

7-6. Major design components

A typical AC generator consists of a stationary stator and a rotor mounted within the stator. The stator contains a specific number of coils, each with a specific number of windings. Similarly, the rotor consists of a specific number of field poles, each with a specific number of windings. In addition to the rotor and stator, a generator has a collector assembly (usually consisting of collector slip rings, brushes, and brush holders). DC flows from the exciter, through the negative brush and slip ring, to the rotor field poles. The return path to the exciter is through the positive brush and slip ring.

a. Rotor. The rotor contains magnetic fields that are established and fed by the exciter. When the rotor is rotated, AC is induced in the stator. The changing polarity of the rotor produces the alternating characteristics of the current. The generated voltage is proportional to the strength of the magnetic field, the number of coils (and number of windings of each coil), and the speed at which the rotor turns.

b. Stator. The frame assembly is the main component of the stator. Insulated windings (or coils) are placed in slots near an air gap in the stator core. There is a fixed relationship between the unit's number of phases and the way the coils are connected. The stator in a four wire, three-phase unit has three sets of armature coils which are spaced 120 electrical degrees apart. One end of each coil is connected to a common neutral terminal. The other end of each coil is connected to separate terminals. Conductors attached to the four terminals carry the current to the system's switchgear and on to the load.

c. Collector slip rings. Slip rings are usually made of non-ferrous metal (brass, bronze or copper); iron or steel is sometimes used. Slip rings usually do not require much servicing. The wearing of grooves or ridges in the slip rings is retarded by designing the machine with limited endplay and by staggering the brushes. Surfaces of the slip rings should be bright and smooth; polishing can be performed with fine sandpaper and honing stone. Electrolytic action can occur at slip ring surfaces producing formation of verdigris. Verdigris is a greenish coating that forms on non-ferrous metals. Electrolytic deterioration can be prevented by reversing the polarity of the slip rings once or twice a year. The stator of the three wire, three-phase unit also has three sets of armature coils spaced 120 electrical degrees apart. The ends of the coils are connected together in a delta configuration. Conductors are attached to the three connecting points.

d. Exciters. An AC or DC generator requires direct current to energize its magnetic field. The DC field current is obtained from a separate source called an exciter. Either rotating or static-type exciters are used for AC power generation systems. There are two types of rotating exciters: brush and brushless. The primary difference between brush and brushless exciters is the method used to transfer DC exciting current to the generator field. Static DC excitation for the generator fields is provided in several forms including field flash voltage from storage batteries and voltage from a system of solid-state components. DC generators are either separately excited or self excited

e. Field flashing. Field flashing is required when generator voltage does not build up and the

generating system (including the voltage regulator) does not have field flash capability. This condition is usually caused by insufficient residual magnetism in the exciter and generator fields. In some cases, a generator that has been out of service for an extended period may lose its residual magnetism and require flashing. Residual magnetism can be restored by flashing the field, thereby, causing a current surge in the generator. Refer to the voltage regulator manufacturer's literature for procedural instructions. Solid-state components may be included in the voltage regulator. Perform field flashing according to the manufacturer's instructions to avoid equipment damage.